# A Note on the Efficiency of the Cochrane-Orcutt Estimator of the AR(1) Regression Model

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ON THE TREATMENT OF THE WEIGHTED INITIAL OBSERVATION IN THE AR(1) REGRESSION MODEL

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# On the Treatment of the Weighted Initial Observation in the AR(1) Regression Model

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A number of studies have investigated the treatment of the weighted initial observation in the estimation of the AR(1) regression model, [e.g., Kadiyala (1968), Maeshiro (1976, 1979), Chipman (1979), Doran (1979), Doran and Griffiths (1983), Spitzer (1979) and Fomby and Guilkey (1983)]. It is generally conceded that the Cochrane-Orcutt (C-O) estimator, which deletes the initial observation, is inefficient relative to the Prais-Winsten (P-W) estimator, which weights it by $(1-\rho^2)^{1/2}$. Nevertheless, it is usually suggested that the C-O estimator might be preferable in cases where the past is not sufficiently long to warrant the use of the P-W estimator, [e.g., Judge, et. al, (1980) p. 182].[1/]

The purpose of this paper is to present a general AR(1) model for the case where the past is finite, to present the efficiencies of the P-W and C-O estimators for this model and to demonstrate that the P-W estimator is always more efficient than the C-O estimator when the AR(1) process has a finite past.

## 2. A General AR(1) Model

Consider the model

(1) $Y = X\beta + \varepsilon$,

where Y is a nx1 vector of observations on the dependent variable, X is a nxk matrix of known nonstochastic regressors, $\beta$ is a kx1 vector of unknown coefficients and $\varepsilon$ is a nx1 vector of random disturbances. Assume that

$$(2)\ \varepsilon_t = \begin{cases} \rho\varepsilon_{t-1} + u_t & t > -q \\ u_t & t \leq -q \end{cases}$$

where $u_t$ is nid(0, $\sigma_u^2$).2/ The parameter q is assumed known and is continuous for $q \geq 1$; q-1 denotes the number of periods since the process began.3/

It is easy to show that

$$E(\varepsilon\varepsilon') = \frac{\sigma_u^2}{1-\rho^2}\,\phi,$$

where

$$\phi^{-1} = \frac{1}{1-\rho^2}\begin{bmatrix} \mu & -\rho & 0 & 0 & \cdots & 0 & 0 \\ -\rho & 1+\rho^2 & -\rho & 0 & \cdots & 0 & 0 \\ 0 & -\rho & 1+\rho^2 & -\rho & \cdots & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & & \cdot & \cdot \\ 0 & 0 & 0 & 0 & \cdots & -\rho & 1 \end{bmatrix}$$

and where $\mu = (1-\rho^{2(q+1)})/(1-\rho^{2q})$.

Furthermore, there is a transformation matrix

$$C = \begin{bmatrix} \delta & 0 & 0 & \cdots & 0 & 0 \\ -\rho & 1 & 0 & \cdots & 0 & 0 \\ 0 & -\rho & 1 & \cdots & 0 & 0 \\ \cdot & \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & \cdot & & \cdot & \cdot \\ 0 & 0 & 0 & \cdots & -\rho & 1 \end{bmatrix}$$

where $\delta = [(1-\rho^2)/(1-\rho^{2q})]^{1/2}$, such that $C'C = (1-\rho^2)\phi^{-1}$. Thus, equation (1) can be transformed to the classical regression model by premultiplying (1) by C.

If the customary stationarity condition is assumed (i.e., $|\rho| < 1$), then the usual covariance matrix, A, is

$$\lim_{q\to\infty} \phi = A,$$

and the usual P-W transformation matrix, M, is

$$\lim_{q\to\infty} C = M.$$ 4/

The C-O transformation matrix, Q, is C with the first row deleted.

### 3. The Relative Efficiencies of the C-O and P-W estimators

It is easy to show that the efficiency of the P-W estimator relative to the general Aitken's estimator is less than the efficiency of the C-O estimator relative to the Aitken's estimator. To see this, let $\tilde{\beta}$, $\hat{\beta}$ and $\hat{\hat{\beta}}$ denote the general Aitken's, P-W and C-O estimators of $\beta$, respectively. The efficiencies of $\hat{\beta}$ and $\hat{\hat{\beta}}$ with respect to $\tilde{\beta}$ are

$$E_{\hat{\beta}} = \frac{|\Sigma_{\tilde{\beta}}|}{|\Sigma_{\hat{\beta}}|} ,$$

and

$$E_{\hat{\hat{\beta}}} = \frac{|\Sigma_{\tilde{\beta}}|}{|\Sigma_{\hat{\hat{\beta}}}|} ,$$

where $\Sigma_{\tilde{\beta}}$ , $\Sigma_{\hat{\beta}}$ and $\Sigma_{\hat{\hat{\beta}}}$ are their respective covariance matrices. But

$$\Sigma_{\tilde{\beta}} = \frac{\sigma_u^2}{1-\rho^2} (X'\phi^{-1}X)^{-1} ,$$

$$\Sigma_{\hat{\beta}} = \frac{\sigma_u^2}{1-\rho^2}(X'M'MX)^{-1}X'M'M\phi M'MX(X'M'MX)^{-1}$$

and

$$\Sigma_{\hat{\hat{\beta}}} = \frac{\sigma_u^2}{1-\rho^2} (X'Q'QX)^{-1}X'Q'Q\phi Q'QX(X'Q'QX)^{-1}.$$

By straightforward multiplication,

$$M'M = (1-\rho^2)\ A^{-1},$$

$$Q'Q = (1-\rho^2)\ (A^{-1}-\theta),$$

$$M\phi M' = (1-\rho^2)(I-\zeta),$$

and

$$Q\phi Q' = (1-\rho^2)\ I,$$

where $\theta$ and $\zeta$ are nxn matrices whose (1,1) elements are 1 and $\rho^{2q}$, respectively, and all other elements are zeros. Given these results, the efficiency ratios can be rewritten as

$$E_{\hat{\beta}} = \frac{|X'(A^{-1})X|^2}{|X'\phi^{-1}X|\,|X'(A^{-1}-\zeta)X|} ,$$

and

$$E\hat{\hat{\beta}} = \frac{|X'(A^{-1}-\theta)X|}{|X'\phi^{-1}X|} .$$

From a standard theorem in matrix algebra,

$|X'A^{-1}X| > |X'(A^{-1}-\zeta)X|$ or $|X'(A^{-1}-\theta)X|$, so that

$E\hat{\beta} > E\hat{\hat{\beta}}$ .5/

This intuition for this result is quite simple. Maeshiro (1980) has noted that the net gain in efficiency results from the gain in efficiency due to the reduction or elimination of autocorrelation and to the loss of efficiency due to the increased colinearity among the transformed variables.6/ In this instance the P-W estimator induces less colinearity in the transformed variables, enough less to be more efficient than the C-O estimator for any given set of fixed regressor variables.

Since both of these estimators will be most inefficient for smoothly trended data, especially for large positive values of $\rho$, the results for the simple time-trend model

$$y_t = \alpha + \beta t + \varepsilon_t$$

are presented. Following Chipman, let $X = \tau - \frac{n+1}{2} \ell$ where $\tau = (1\ 2\ 3\ \ldots\ n)'$; therefore,

$$X'A^{-1}X = \frac{(n-1)\ g\ (\rho,\ n)}{12\ (1-\rho^2)},$$

where $g(\rho,n) = (n-3)(n-2)\rho^2 - 2(n-3)(n+1)\rho + n(n+1)$.

By direct multiplication,

$$X'\phi^{-1}X = X'A^{-1}X + \left(\frac{n-1}{2}\right)^2 \rho^{2q}/(1-\rho^{2q}),$$

$$X'(A^{-1}-\theta)X = X'A^{-1}X - \left(\frac{n-1}{2}\right)^2$$

and

$$X'(A^{-1}-\zeta)X = X'A^{-1}X - \left(\frac{n-1}{2}\right)^2 \rho^{2q} ,$$

Thus, for the time-trend model

$$E_{\hat{\beta}} = \frac{\left[\frac{(n-1)\, q\, (\rho,n)}{12\,(1-\rho^2)}\right]^2}{\left[\frac{(n-1)q(\rho,n)}{12\,(1-\rho^2)} + \left(\frac{n-1}{2}\right)^2 \left(\frac{\rho^{2q}}{1-\rho^{2q}}\right)\right]\left[\frac{(n-1)q(\rho,n)}{12\,(1-\rho^2)} - \left(\frac{n-1}{2}\right)^2 \rho^{2q}\right]} .$$

Likewise,

$$E_{\hat{\hat{\beta}}} = \frac{\frac{(n-1)g(\rho,n)}{12\,(1-\rho^2)} - \left(\frac{n-1}{2}\right)^2}{\frac{(n-1)g(\rho,n)}{12\,(1-\rho^2)} + \left(\frac{n-1}{2}\right)^2 \frac{\rho^{2q}}{1-\rho^{2q}}} .$$

Also,

$$\lim_{q\to\infty} E_{\hat{\hat{\beta}}} = \frac{\frac{(n-1)g(\rho,n)}{12\,(1-\rho^2)} - \left(\frac{n-1}{2}\right)^2}{\frac{(n-1)g(\rho,n)}{12\,(1-\rho^2)}} .$$

Values of these efficiencies are presented in Tables 1 and 2. As expected, both estimators are relatively inefficient for large positive values of $\rho$. The inefficiency diminishes quickly, however, for the P-W estimator as q gets large.

## 4. Conclusions

This paper has shown that the Prais-Winston estimator is more efficient than the Cochrane-Orcutt estimator if the usual AR(1) model is assumed to have a finite past. Thus, the usual assumption that the latter estimator is preferred in this case is shown to be wrong. Calculated efficiency ratios for the time-trend model suggest that the difference in the efficiency of the two estimators might be substantial for smoothly trended data. These results give further support to the growing belief that whenever possible the first observation should be retained in the serial correlation adjustment.

## FOOTNOTES

1/ Since economic time series are generally prices or quantities of commodities most (if not all) of which are the result of inventions, innovations or deregulation that have occurred in the finite past, this assumption is, strictly speaking, not valid. Nevertheless, it is reasonable to conjecture that the loss of efficiency may be small if the initial observation of the sample is "sufficiently far" from the initial observation in the time series. The results for the mean and time-trend models are consistent with this conjecture.

2/ There are of course an infinite number of other finite past assumptions that could be made. For example, let $\varepsilon_t$ be nid(0, $\sigma_\varepsilon^2$) for $t \leq -q$ and let $u_t$ be nid(0, $\sigma_u^2$) for $t > q$, and further assume that $\sigma_\varepsilon^2 = \sigma_u^2/(1-\rho^2)$. This would eliminate the heteroskedasticity in (2), but it would also eliminate the need to distinguish between the finite and infinite past that is characteristic of nearly all discussions of the AR(1) regression model. Thus, attention is limited to the generalization of the usual model.

3/ If one wished to use the feasible Aitken's estimator, q would have to be estimated simultaneously with $\rho$. If the wrong value of q is used, it can be shown that the resulting estimator may be more or less efficient than the C-O estimator. However, the C-O estimator is less efficient for the time-trend model.

4/ Readers unfamiliar with the form of these matrices can consult Kadiyala (1969) or Judge, et. al. (1981, p. 181).

5/ See Graybill (1969, p. 330).

6/ See Kramer (1982) for some additional insight.

Table 1: Calculated Values of $E_{\hat{\beta}}$ for Time-Trend Model

| | | n | | | | |
|---|---|---|---|---|---|---|
| q | ρ | 10 | 20 | 50 | 100 | 250 |
| | -0.99 | 0.924565 | 0.963070 | 0.985369 | 0.992705 | 0.997086 |
| | -0.50 | 0.992507 | 0.996051 | 0.998369 | 0.999176 | 0.999668 |
| | -0.20 | 0.999753 | 0.999857 | 0.999937 | 0.999968 | 0.999987 |
| | 0.20 | 0.999639 | 0.999745 | 0.999872 | 0.999931 | 0.999971 |
| | 0.50 | 0.979974 | 0.982597 | 0.989273 | 0.993688 | 0.997203 |
| 1 | 0.75 | 0.847964 | 0.848728 | 0.870911 | 0.906280 | 0.950776 |
| | 0.90 | 0.576887 | 0.541784 | 0.539708 | 0.562906 | 0.658873 |
| | 0.95 | 0.442701 | 0.358381 | 0.325852 | 0.326317 | 0.361145 |
| | 0.97 | 0.387519 | 0.280292 | 0.219723 | 0.211732 | 0.218260 |
| | 0.98 | 0.360330 | 0.242681 | 0.166204 | 0.149160 | 0.147969 |
| | 0.99 | 0.333661 | 0.207003 | 0.116815 | 0.087616 | 0.077203 |
| | -0.99 | 0.99383 | 0.99709 | 0.99887 | 0.99944 | 0.99978 |
| | -0.50 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | -0.20 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | 0.20 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | 0.50 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| 10 | 0.75 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | 0.90 | 0.99644 | 0.99590 | 0.99586 | 0.99623 | 0.99748 |
| | 0.95 | 0.97070 | 0.95273 | 0.95273 | 0.95283 | 0.95931 |
| | 0.97 | 0.93599 | 0.90000 | 0.86680 | 0.86125 | 0.86581 |
| | 0.98 | 0.90728 | 0.84771 | 0.77591 | 0.75280 | 0.75104 |
| | 0.99 | 0.86806 | 0.77426 | 0.63475 | 0.55787 | 0.52364 |
| | 0.99 | 0.99772 | 0.99893 | 0.99958 | 0.99979 | 0.99992 |
| | -0.50 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | -0.20 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | 0.20 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | 0.50 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| 20 | 0.75 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | 0.90 | 0.99995 | 0.99995 | 0.99995 | 0.99995 | 0.99997 |
| | 0.95 | 0.99715 | 0.99596 | 0.99533 | 0.99534 | 0.99600 |
| | 0.97 | 0.98707 | 0.97916 | 0.97141 | 0.97007 | 0.97117 |
| | 0.98 | 0.97341 | 0.95419 | 0.92834 | 0.91932 | 0.91861 |
| | 0.99 | 0.94703 | 0.90311 | 0.82526 | 0.77421 | 0.74920 |
| | -0.99 | 0.99964 | 0.99983 | 0.99993 | 0.99997 | 0.99999 |
| | -0.50 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | -0.20 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | 0.20 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| 50 | 0.50 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | 0.75 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | 0.90 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | 0.95 | 0.99999 | 0.99999 | 0.99999 | 0.99999 | 0.99999 |
| | 0.97 | 0.99975 | 0.99959 | 0.99944 | 0.99941 | 0.99943 |
| | 0.98 | 0.99846 | 0.99729 | 0.99565 | 0.99506 | 0.99501 |
| | 0.99 | 0.99133 | 0.98350 | 0.96796 | 0.95640 | 0.95027 |

Table 2: Calculated Values of $E_{\hat{\beta}}$ for the Time-Trend Model

| q | ρ | n = 10 | 20 | 50 | 100 | 250 |
|---|---|---|---|---|---|---|
| | -0.99 | 0.921468 | 0.961555 | 0.984769 | 0.992405 | 0.996967 |
| | -0.50 | 0.870036 | 0.934313 | 0.973503 | 0.986710 | 0.994674 |
| | -0.20 | 0.812656 | 0.901268 | 0.959222 | 0.979391 | 0.991703 |
| | 0.20 | 0.672807 | 0.804607 | 0.912880 | 0.954817 | 0.981524 |
| | 0.50 | 0.497674 | 0.629268 | 0.804975 | 0.892147 | 0.954041 |
| 1 | 0.75 | 0.344461 | 0.357294 | 0.519902 | 0.676713 | 0.838702 |
| | 0.90 | 0.301061 | 0.202016 | 0.191553 | 0.268166 | 0.457843 |
| | 0.95 | 0.300654 | 0.177578 | 0.105880 | 0.107860 | 0.182183 |
| | 0.97 | 0.302590 | 0.173514 | 0.085836 | 0.064457 | 0.082808 |
| | 0.98 | 0.304002 | 0.172777 | 0.079646 | 0.050151 | 0.046660 |
| | 0.99 | 0.305704 | 0.172910 | 0.076171 | 0.041504 | 0.023632 |
| | -0.99 | 0.990772 | 0.995650 | 0.998313 | 0.999164 | 0.999668 |
| | -0.50 | 0.899254 | 0.949912 | 0.979995 | 0.989999 | 0.996000 |
| | -0.20 | 0.818792 | 0.904841 | 0.960790 | 0.980199 | 0.992032 |
| | 0.20 | 0.681729 | 0.810945 | 0.916072 | 0.956546 | 0.982250 |
| | 0.50 | 0.569149 | 0.693548 | 0.846234 | 0.916869 | 0.965130 |
| 10 | 0.75 | 0.544886 | 0.558820 | 0.711597 | 0.826670 | 0.922163 |
| | 0.90 | 0.665712 | 0.539260 | 0.522772 | 0.628820 | 0.796097 |
| | 0.95 | 0.738810 | 0.586893 | 0.437934 | 0.443046 | 0.594441 |
| | 0.97 | 0.770072 | 0.618406 | 0.420224 | 0.347190 | 0.410700 |
| | 0.98 | 0.785696 | 0.636779 | 0.420755 | 0.307085 | 0.291194 |
| | 0.99 | 0.801153 | 0.656707 | 0.430024 | 0.282780 | 0.181318 |
| | -0.99 | 0.994903 | 0.997602 | 0.999071 | 0.999540 | 0.999817 |
| | -0.50 | 0.899254 | 0.949912 | 0.979995 | 0.989999 | 0.996000 |
| | -0.20 | 0.818792 | 0.904841 | 0.960790 | 0.980199 | 0.992032 |
| | 0.20 | 0.681729 | 0.810945 | 0.916072 | 0.956546 | 0.982250 |
| | 0.50 | 0.569149 | 0.693548 | 0.846234 | 0.916869 | 0.965130 |
| 20 | 0.75 | 0.545671 | 0.559600 | 0.712246 | 0.827123 | 0.922390 |
| | 0.90 | 0.690742 | 0.567608 | 0.551291 | 0.655182 | 0.814090 |
| | 0.95 | 0.793502 | 0.658700 | 0.514201 | 0.519381 | 0.665683 |
| | 0.97 | 0.837938 | 0.714437 | 0.528067 | 0.450866 | 0.518284 |
| | 0.98 | 0.859430 | 0.745129 | 0.547782 | 0.424973 | 0.406561 |
| | 0.99 | 0.879870 | 0.776666 | 0.578333 | 0.418702 | 0.287049 |
| | -0.99 | 0.997332 | 0.998747 | 0.999515 | 0.999760 | 0.999905 |
| | -0.50 | 0.899254 | 0.949912 | 0.979995 | 0.989999 | 0.996000 |
| | -0.20 | 0.818792 | 0.904841 | 0.960790 | 0.980199 | 0.992032 |
| | 0.20 | 0.681729 | 0.810945 | 0.916072 | 0.956546 | 0.982250 |
| | 0.50 | 0.569149 | 0.693548 | 0.846234 | 0.916869 | 0.965130 |
| 50 | 0.75 | 0.545673 | 0.559603 | 0.712248 | 0.827125 | 0.922391 |
| | 0.90 | 0.693908 | 0.571252 | 0.554965 | 0.658532 | 0.816330 |
| | 0.95 | 0.814237 | 0.687643 | 0.546969 | 0.552105 | 0.694308 |
| | 0.97 | 0.874880 | 0.771866 | 0.602103 | 0.426145 | 0.592671 |
| | 0.98 | 0.905367 | 0.820623 | 0.654637 | 0.536281 | 0.517386 |
| | 0.99 | 0.933454 | 0.869453 | 0.724267 | 0.579736 | 0.435373 |
| | -0.99 | 0.998307 | 0.999205 | 0.999692 | 0.999848 | 0.999939 |
| | -0.50 | 0.899254 | 0.949912 | 0.979995 | 0.989999 | 0.996000 |
| | -0.20 | 0.818792 | 0.904841 | 0.960790 | 0.980199 | 0.992032 |
| | 0.20 | 0.681729 | 0.810945 | 0.916072 | 0.956546 | 0.982250 |
| | 0.50 | 0.569149 | 0.693548 | 0.846234 | 0.916869 | 0.965130 |
| ∞ | 0.75 | 0.545673 | 0.559603 | 0.712248 | 0.827125 | 0.922391 |
| | 0.90 | 0.693914 | 0.571259 | 0.554971 | 0.658538 | 0.816344 |
| | 0.95 | 0.815133 | 0.688917 | 0.548440 | 0.553573 | 0.695567 |
| | 0.97 | 0.880116 | 0.780332 | 0.613715 | 0.538274 | 0.604377 |
| | 0.98 | 0.916874 | 0.840620 | 0.686060 | 0.571422 | 0.552765 |
| | 0.99 | 0.956759 | 0.913084 | 0.805571 | 0.685130 | 0.548793 |

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